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Stabilization with Foamed Asphalt of Aggregates Commonly Used in Low-Volume Roads

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Foamed asphalt, which is generated by combining asphalt cement and cold water through a foam nozzle, has been used worldwide as a means of stabilizing pavement construction materials. A review of the literature indicated a successful and broad use of foamed asphalt in low-volume-road construction. This relatively new concept appears to exhibit several characteristics that could lead to increased use of locally available materials as well as a more economical stabilization process without some detrimental features associated with other agents. The effects of different variables on foamed-asphalt mix design (Foamix) were investigated in a laboratory study. An AC-20 asphalt cement was used as the binder material. The aggregates included in the study were outwash sand, pit-run gravel, and crushed stone. The variables studied were foamed-asphalt content (two levels), moisture content (three levels), curing period (three levels), testing temperature (two levels), and mixing temperature (three levels). Foamix was found to be significantly affected by water infiltration. Water-sensitivity results indicated that saturated strengths were much lower than corresponding cured strengths. Specimens fabricated at the highest bitumen content showed a greater resistance to water. In addition, moisture content (at mixing), bitumen content, and total fluid content all proved to have an effect on mixture performance. Foamix strengths increased with curing time, particularly from one to three days. It appears that foamed asphalt can be used as a stabilizing agent for commonly available virgin aggregates as well as recycled material when adequate drainage and/or sealing is provided or when they are located in relatively dry environments.

Engineers have long realized the economic advantages inherent in aggregate stabilization. Many stabilizing agents are now in use, including portland cement, lime, lime-fly ash, and bitumen. This paper will investigate the feasibility of a relatively new bitumen stabilizer known as foamed asphalt.

The foamed-asphalt concept was developed during the mid-1950s by Csanyi of Iowa State University. The potential benefits from this process appeared to be so numerous that interest quickly spread. The applicability of the foaming process is currently being studied and evaluated throughout the world in countries such as Australia, South Africa, New Zealand, Japan, West Germany, and many others. In Australia alone, more than 3.5 million yd² of foamed asphalt have been laid, generally as a base or subbase. Foamed-asphalt construction has also increased in North America as hundreds of miles of surface-course mixtures have been produced (1).

When cold water is introduced to hot paving-grade bitumen, a foamed asphalt is produced. This foamed product has a lower viscosity and a greater effective volume than the original penetration-grade bitumen. The foaming process offers several economic and environmental advantages over competing bitumen stabilizers (Table 1). From a production standpoint, less water is hauled to the construction site, and less asphalt is required than with the use of asphalt emulsion. Therefore, significant energy and transportation savings are realized. In addition, curing of the compacted mix is not required; therefore the roadway can be opened to traffic more quickly. It should also be noted that the curing process that occurs with time is environmentally safe since no harmful hydrocarbons will pollute the atmosphere. Another process benefit is that foamed mixes allow the use of a broader spectrum of aggregates. Marginal soils containing large amounts of fines, often deemed poor for other types of stabilization, as well as recycled pavement material are quite suitable for foamed-asphalt stabilization. Foamed-asphalt mixtures have been found to be very workable. If necessary, the mix can be reworked several days after compaction to achieve specified densities. A major plant advantage is that foamed-asphalt mixtures can be stockpiled. They can be stored up to a year without any detrimental effects (2).

This study approaches the mix design of foamed-asphalt mixes by using strength data obtained by Hveem and Marshall techniques and the resilient-modulus test, among other test parameters. The major concern of this report is the performance and production of bituminous bases that use commonly available pavement materials stabilized by means of the not-so-well-known technique of foamed-asphalt stabilization.

Foamed-asphalt stabilization permits the combined use of the most prominent factors related to both cold and hot mix methods. Asphalt cement when used as a foam and not in its liquid form (heated) increases its volume as much as 13-29 times (3-5). Less of this material is expected to be required to achieve the same characteristics as those obtained from conventional hot mix. The use of cold, wet aggregate will eliminate the use of energy required for the drying process. However, due to the complexity of the mix behavior under different loading and environmental conditions, a more thorough understanding of the role of each of the foamed-asphalt-stabilized base components is needed.

EVALUATION OF FOAMED-ASPHALT CHARACTERISTICS

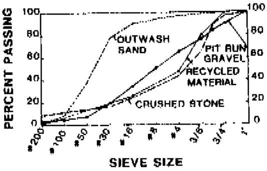
The testing of asphalt cements for suitability of foaming should be performed in the laboratory prior to the utilization of this material in preparing the mix. There are no records to suggest any asphalt cement that cannot be foamed unless there are trace amounts of silicone present. It seems that foaming is always possible by proper selection and adjustment of nozzle and proper steam, water, air, and asphalt pressure, according to the method being used. The deleterious effects of trace amounts of silicone can be overcome with the addition of certain metallic stearates. The process of foaming asphalt was developed by Csanyi (1959), who used low-pressure steam injected concurrently with the hot asphalt to generate a foam prior to its contact with the aggregate. The original process was slightly modified in 1970 by Mobil Oil Company in an effort to simplify field control practices. The modified procedure, which is most often used today, involves the introduction of water under a controlled flow rate into hot bitumen. A foamed state is produced when approximately 2 percent of water is added to hot [approximately 325°F (160°C)] penetration-grade bitumen in the foaming chamber. Continental Oil Company (CONOCO) has developed advanced procedures and a foamed-asphalt dispenser for foaming the asphalt used in laboratory investigations.

Information concerning the foam properties of asphalt cements is often reported in terms of foam or expansion ratio (ratio of foam volume to the volume of the asphalt cement before foaming) and half-life of the foam (the time that elapsed from the moment that the foam was at its maximum volume to the time that it reached half of this volume).

Table 1. Asphalt-cement mixing methods.

Method	Aggregate	Asphalt Cement	Laydown	Haul	Special Processing of Asphalt
Hot mix	Hot	Hot	Hot, dry	Asphalt, 100 percent	No
Emulsion mix	Cold	Cold	Cold, wet	Asphalt, 50-70 percent Water, 40-30 percent	Yes
Foam mix	Cold	Hot	Cold, wet	Asphalt, 100 percent	No

Figure 1. Aggregate gradations of base-course materials used.



In 1978, Abel (6) concluded after analyzing asphalt cements of different viscosities and from different sources, with and without an antifoaming agent (silicone) and antistripping additives, that

1. Asphalts with silicone do not foam satisfactorily;
2. The lower-viscosity asphalts foamed more readily than the higher-viscosity asphalts;
3. Antistripping additives increased the foam factor (expansion ratio); however, this effect appeared to be temporary probably because high heat tends to destroy most agents; and
4. Asphalt-cement temperatures have to be at least 300°F (149°C) to produce acceptable foam.

It is clear that the source, viscosity (grade), additives, and temperature of the asphalt cement can all affect the characteristics, quality, and quantity of the foam produced. Brennan and others (4), in a study conducted at Purdue University in 1980, reported similar findings. In this study, expansion ratio and half-life were measured to compare the foaming characteristics of different asphalts marketed in Indiana. Half-life and expansion ratio were affected primarily by the amount of foam produced, the amount of water in the foam, and the foaming temperature of the asphalt. In general, increasing the foaming temperature increased the expansion ratio but to the detriment of the half-life.

The amount of water used to foam the hot asphalt cement had the same effect. Therefore, a trade-off of half-life for expansion ratio, or vice versa, was suggested (3,4) for the selection of the most suitable asphalt cement to be used as the stabilizing agent in Foamix.

Reasonable limits for an expansion ratio of 6-12 and a half-life of 40-80 s are reported and recommended by Mitvalsky (3). As a result of his investigation, Brennan (4) selected asphalt cements with expansion ratios as high as 20 and a half-life around 30 s. Ratios of expansion ratio to half-life of 4.5/102 s, 9.0/55 s, and 13/20 s are common in the literature (3,4,6).

LABORATORY STUDY

Detailed laboratory investigations were performed to characterize the performance of foamed asphalt as a stabilizing agent. The objective of these studies was to develop guidelines for a mix design procedure.

Equipment

The equipment used for the fabrication and testing of foamed-asphalt mixtures in the laboratory is one of the major contributors to the quality of the finished samples and the accuracy of the test results. The main items of equipment used were as follows:

1. Laboratory Foamix asphalt dispenser developed by CONOCO (primarily consists of 2-gal storage tank, control panel, and outlet nozzle);
2. Hveem or California kneading compactor;
3. Diametral resilient-modulus device;
4. Hveem stabilometer and compression machine;
5. Marshall equipment; and
6. Mechanical mixer, ovens, and other equipment.

Materials

Bituminous Material

A laboratory analysis of the foaming characteristics of various asphalt cements from different sources (4) concluded that the asphalt cement graded AC-20 was the most suitable for use in this study. It was shown that, in general, the asphalt cement AC-20 obtained from Whiting, Indiana, that had an expansion ratio greater than 12 times its original volume took as long as 13 s to reduce the foam by 50 percent when foamed with 2 percent by asphalt flow of cold water and at a temperature of 325°F. The properties of this binder material are listed below [1 mm = 0.04 in; 1 cSt = 0.01 cm²/s; t°F = (t°C ÷ 0.55) + 32]:

Property	Amount
Penetration (mm)	0.42
Kinematic viscosity (cSt) at	
330°F	229
325°F	126
350°F	72

Aggregates

There were four different materials used in this study: a recycled material, a mixture of sand and gravel known as pit-run gravel, a crushed limestone, and a sand known as outwash sand. All these aggregates are commonly used as base-course materials in Indiana. Their respective gradations are presented in Figure 1.

Experimental Procedure

The main concern of this study was the analysis of the suitability of cold-mix foamed-asphalt mixtures as a stabilized base or subbase course for pavements. The variables measured were intended to give indications of the quality of performance of these mixtures as well as to serve as an aid in the development of design procedures for the use of foamed asphalt as a stabilizing agent. Stabilization is a process in which the behavior properties of the material are improved for its intended use. Many laboratory and field studies have shown that successful stabilization is produced with design and construction techniques that properly consider the factors that affect the performance of an asphalt mix. A summary of all the factors considered in the mixing and preparation of all mixtures used in this study is presented below:

Variable	No. of Levels
Foamed-asphalt content	2
Mixing-water content	3
Mixing temperature	3
Testing temperature	2
Curing time	3
Water sensitivity	1

Two types of asphalt content per aggregate type were considered. Several sets of specimens were mixed with trial asphalt contents recommended by CONOCO's proposed mix design (7). The optimum amount of mixing water for each respective aggregate was somewhere in the "fluff-point" range of the mineral material. This moisture content brings the material to its maximum volume consistent with easy manipulation (8). The mixing water used with the recycled material was less, 1 percent by dry weight of the aggregate. The densities of trial mixes at different combinations of foamed asphalt and moisture content lead to the selection of the final levels of both variables to be used.

Three mixing and two testing temperatures were used during this study. One, three, and seven days were the curing-time levels considered. The effect of moisture on the mixture performance was evaluated by using a modified water-sensitivity test modeled after a method suggested by the Asphalt Institute.

Testing Procedure

The following section contains a brief description of the principal test procedures as well as test conditions that were considered in this laboratory study. The samples tested (three specimens per set), made of four different types of aggregate with their respective foamed-asphalt and initial mixing water contents, were mixed at three different temperatures--50, 72, and 100°F (10, 22, and 38°C)--and tested at two temperatures--72 and 50°F. All the samples were cured at room conditions (72°F) for one, three, and seven days. All the specimens were extruded from the molds one day following compaction. This period of time permitted the specimens to gain some strength for easy handling during the extrusion and testing process.

The unit weight at time of compaction, which is a measure of the compactibility of the foamed-asphalt mixture during field construction, is a useful parameter in the mix evaluation. High unit weights achieved during construction are recommended in order to reduce further compaction by traffic, which can lead to rutting of the pavement. On the other hand, a certain amount of air voids in the mix is needed to increase drainage and curing rate of the base-course material. This parameter was obtained by the saturated surface-dry bulk-specific-gravity method (ASTM D 2726) and by measuring the weight in air and the height of the test specimens.

One of the common dynamic tests used to determine the resilient characteristics of the pavement material is the method of diametral loading. The resilient-modulus test was performed following procedures developed by Schmidt. A pulsating load of 50 lbf was applied to a specimen across its vertical diameter every 3 s with a duration of 0.1 s.

Since Indiana uses the Hveem test in the design of asphalt mixtures, the foamed-asphalt mixes were also characterized by means of the Hveem stabilometer. Resistance R-values and modified Hveem stability values were obtained with dry and water-saturated samples. Recycled material samples were tested by using the Marshall apparatus.

TEST RESULTS AND DISCUSSION

The study evaluated the foamed-asphalt mix strength of both cured specimens and saturated specimens, as mentioned before. Observations were made during the several stages of the mix production (mixing, curing, etc.) in order to develop a mix design procedure for foamed-asphalt mixes. A summary of the test results and observations obtained from this laboratory study is presented next.

Mixing and Coating

Foamed asphalt was observed to have good mixing properties with the different aggregates used in this study. Although mixing seemingly became more difficult as moisture and bitumen content increased, no problems such as stickiness or lumping were encountered. Foamed-asphalt specimens could be described as having a homogeneous, black-speckled appearance. Current theory, which suggests that foamed asphalt selectively coats the fine particles, appears to be valid. An increase in bitumen content simply produced darker samples with the same partial coating (8).

Compaction

The foamed-asphalt mixes became easier to compact as the amounts of moisture and bitumen were increased. It appears that a total fluid content (percent moisture plus percent bitumen) near the soil's optimum moisture content, as determined by ASTM D 698, produces the best compactive conditions. This was the case for the sand, gravel, and limestone mixes, which were prepared in the Hveem kneading compactor. The recycled mixes were prepared by adding foamed asphalt to the cold and wet salvaged material and then compacting it with the Marshall hammer or the gyratory machine. Initial trial mixes indicated that gyratory compaction was more suitable for the recycled mixes at room temperature. Figure 2 presents the various densities obtained when the recycled mixes were compacted with both methods by using different foamed-asphalt contents. Figure 3 shows the effect of the initial moisture content, the foamed-asphalt content, and curing time on the density or unit weight of crushed-stone mixes. The values observed in this graph were similar to the ones obtained by using sand and gravel. As can be seen in Figure 4, different amounts of foamed asphalt were introduced to crushed stone and gravel and mixed at their "fluff-point" initial mixing water content. The foamed-asphalt content that gave the densest mixes was then used throughout the rest of the study.

The first criterion evaluated was the resilient modulus of the samples. The graphs shown in this paper were selected from a multitude of graphs and are considered to be typical and representative of general trends and behavior of all the foamed-asphalt mixes analyzed.

Resilient Modulus

Figure 5 presents a graph of resilient modulus

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Figure 2. Density of recycled material.

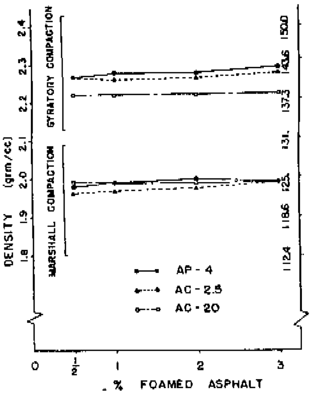


Figure 3. Unit weight versus mixing water.

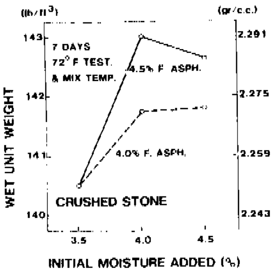


Figure 4. Unit weight versus binder content.

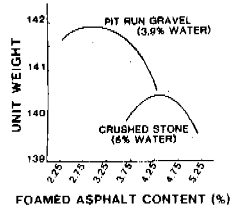
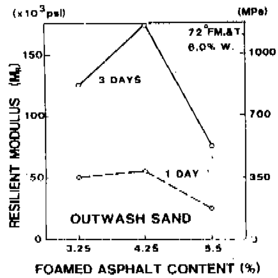


Figure 5. Binder content and curing versus M_R.



versus bitumen content for outwash sand Foamix at 6.0 percent mixing water content for one- and three-day cured samples. Past studies by Bowering (9) and Ruckel (10), among others, found that with increasing bitumen content, resilient modulus, Hveem stabilometer values, California bearing ratio, and other strength parameters all reached maximum values at an intermediate binder content and then decreased. The trend shown in Figure 5 was therefore anticipated and resembles the typical results found for the other foamed-asphalt mixes. The effects of curing time can be observed here; three-day cured specimens have a higher resilient modulus than one-day cured samples.

The effects of testing temperature and curing time are shown in Figures 6 and 7 for pit-run gravel Foamix, prepared at its optimum binder content and mixing moisture content (fluff point). Low temperatures resulted in higher resilient moduli than for samples tested at normal room conditions for all the materials used in this study.

It was observed that, in general, the curing time period affects the strength behavior of the mixtures. The mixes gained most of their strength in the first three days when cured under normal conditions. Figure 8 depicts the same conclusion stated before but by using the Hveem R-value of the mix prepared at three different mixing moisture contents.

The effects of different mixing temperatures (Figure 9) were compared for Foamix prepared at various levels of asphalt content as well as with various curing conditions. It appears that increasing the mixing temperature resulted in improved coating of the aggregate particles and therefore stronger mixes are obtained.

Figure 10 presents the Marshall stabilities of a recycled mix for different foamed-asphalt contents and curing conditions. It is noted that for the "as-is" tests (one and seven days), the optimum stability occurred when 0.5 percent binder was added. For the water-sensitivity test, optimum stability occurred when 1 percent asphalt was added.

The analysis of the results in this study also considered the effects of the water-saturation test. Comparisons were made between average test values for soaked and unsoaked samples of foamed-asphalt mixes (see Figures 7, 10, and 11). It was noted that Foamix was significantly affected by the water. Three- and seven-day cured gravel samples had their resilient-modulus values reduced as much as 70 percent from the original "dry" values (Figure 11). Water affected specimens of sand, gravel, and crushed stone cured for only one day more drastically (see Figure 7).

FOAMED-ASPHALT APPLICATIONS

In-place bituminous soil stablilization by using foamed asphalt was first described by Csanyi in Iowa in 1956. The original method, which used low-pressure steam instead of water under pressure, was used for field applications in Arizona (1960) and in Nipawin in Canada (11). The improved method developed by Mobil Oil of Australia in 1968 makes the foamed-asphalt technique more practical and economical to use in construction. Conventional equipment

Figure 6. Testing temperature versus M_R.

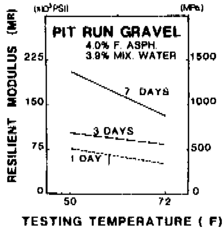


Figure 7. Curing time versus M_R.

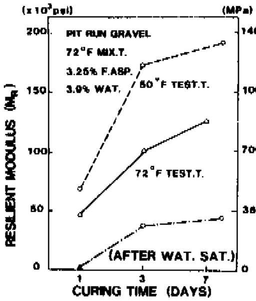


Figure 8. Curing time versus Hveem R-value.

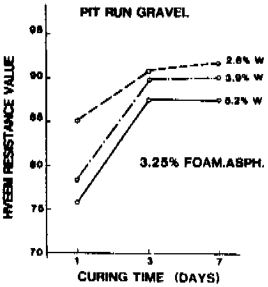


Figure 9. Mixing temperature versus Hveem S-value.

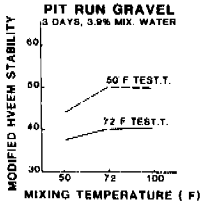


Figure 10. Marshall stability versus asphalt content (recycled material).

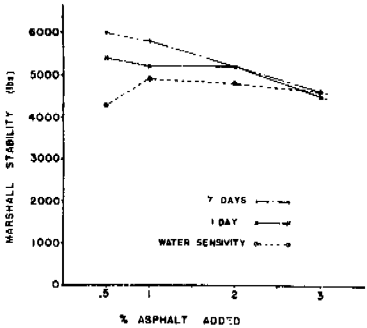
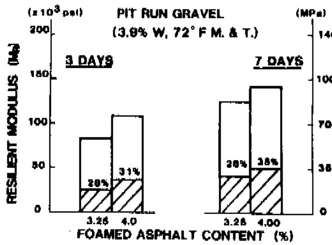


Figure 11. Binder content versus M_R (water saturated).



can be used with only minor modifications.

Since 1970, foamed asphalt has been used as a binder in bituminous stabilization projects in Australia (12), South Africa (13), England, Germany, France, Egypt, and several other countries. CONOCO obtained the marketing rights for the United States after 1970 and also developed a laboratory foam generator to facilitate the study of this new stabilization technique. Foamed asphalt has since been used in various states, among them Colorado (1), North Dakota, Virginia, Pennsylvania, Michigan, Oklahoma, and others (5).

Foamed-asphalt base courses have been overlaid by fog sealing, slurry seals, and more widely by a thin asphalt-concrete layer. Base-course material has also been mixed in place and at a central plant. It has been reported that construction procedures did not cause any serious problems or major equipment changes. Finally, the review of research studies performed in these states and countries mentioned before provides a broad range of data from a variety of aggregates and test procedures. Generally, the different methods of investigation cover the selection, proportioning, and testing of the components involved in the production of foamed-asphalt paving mixtures. The aggregate characterization; the determination of different asphalt-cement foaming characteristics; the selection of the variables that will be measured; and the proportioning, mixing, and preparation and curing of the mixtures are the different steps and sequences followed in most of the reported studies performed for foamed-asphalt mixes.

CONCLUSIONS

Based on this laboratory study and on field measurements reported in the references, foamed-asphalt stabilized materials are reported to have the following environmental, applicational, and economic advantages:

1. Roadway base courses can be effectively stabilized by this process. Foamed-asphalt base and subbase construction is a viable alternative to plant mix bituminous base.
2. This process is relatively simple and does not require a major investment in new equipment. Standard equipment can be used in continuous plants, for in situ mixing, and in drum dryer mixers with minimum modification.
3. Binder costs are not increased by dilutents and additional manufacturing costs. No dilutents as in cutbacks or water in emulsions have to be hauled from the source to the mixing plant.
4. Minimum pollution problems are created when foamed asphalt is used in asphalt recycling and other applications. The process is ecologically desirable. There are reduced energy demands in the production of Foamix. Foamix permits the widespread use of marginal aggregates.
5. No aeration or curing is required before compaction. The foamed-asphalt mix can be compacted immediately after laydown and can be quickly opened to light traffic.
6. Cold mix base courses can be produced with cold, wet, and marginal aggregates as well as with aged recycled pavement material.
7. The mix can be stockpiled and placed at a later time. The mix is not subjected to leaching of the binder by rain. Once placed, the mixture can also be reworked easily after several days.
8. Laboratory investigations as well as test results from field samples suggest that the same or higher stability values of the Foamix can be achieved with a lower binder content than conventional mixes.

These potential advantages for producing low-cost pavement mixtures are reported for foamed-asphalt mixtures under different types of test procedures, aggregates used, and environmental as well as load conditions. However, based on the studies discussed in this paper, it was also concluded that foamed-asphalt mixtures do not appear suitable for high-quality wearing courses since the lack of coating of the large aggregates would probably cause raveling of the surface. The design procedure for use of foamed asphalt has not been fully developed; however, it is suggested that procedures recommended elsewhere (8,10) be followed. The moisture susceptibility of the mixture should be carefully and realistically analyzed, since the durability of foamed-asphalt mixes appears to be low when they are subjected to this type of exposure.

ACKNOWLEDGMENT

The contents of this paper reflect our views and we are responsible for the facts and accuracy of the data presented here. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This paper does not constitute a standard, specification, or regulation.

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